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THE RATES OF ASCENT AND DESCENT OF FREE BALLOONS, AND THE EFFECTS OF RADIATION ON RECORDS OF TEMPERATURE IN THE UPPER AIR

By L. H. G. DINES, M.A.

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THE RATES OF ASCENT AND DESCENT OF FREE BALLOONS, AND THE EFFECTS OF RADIATION ON RECORDS OF TEMPERATURE IN THE UPPER AIR

By L. H. G. DINES, M.A.

The purpose of this paper is firstly to discuss the question of the rates of ascent and descent of the sounding balloons used by the Upper Air Section of Kew Observatory, and secondly the allied question of the effect of insolation on the record of temperature made by the meteorograph at heights of 13 Km. and over. The connexion between the two is a vital one, because in making soundings with small free balloons it is the universal practice to ventilate the thermograph by a current of air induced by the vertical velocity relative to the surrounding air.

I.—The vertical Velocity of small free rubber Balloons

The new work in this paper is primarily based on observations made with sounding balloons in England ; it is therefore necessary to describe briefly the form of the apparatus used. A full description will be found in a pamphlet, " The Dines balloon meteorograph and the method of using it." (1)* Briefly, a rubber balloon is inflated with hydrogen to a diameter of a meter or more, a long string is attached to the neck, carrying a light meteorograph at the lower end secured in the middle of a light framework of thin bamboo strips, stayed by cotton threads. The balloon rises until it bursts, when the whole apparatus falls under the action of gravity and air resistance ; no parachute is employed to check the fall. No clock is used in the Dines meteorograph, so that the velocity of ascent or descent cannot be determined from the record. An illustration of the meteorograph and bamboo frame is given in Fig. 1.

Balloon soundings of this kind have been made in England, with minor modifications only, for the last 27 years. The balloons employed have varied in weight from about 200 gm. to 800 gm. ; the weight of the instrument and bamboo frame has tended to increase as time has gone on, and now is usually about 140 or 150 gm.

The problem of estimating beforehand how fast a small balloon will rise when the weight and free lift are known is not an easy one. Several workers have turned their attention to it, but no one has yet succeeded in discovering a full explanation of the experimental data which have been accumulated. Several purely empirical formulae have been evolved by different authorities from time to time, each for the most part being limited to a narrow range of conditions. It is always found that there is a large amount of scatter among the individual observations, and that a great number are required before a reliable mean can be formed. The most comprehensive paper on the subject is one by Hesselberg and Birkeland (2).

The new work in the present paper refers entirely to the larger balloons used for sounding purposes as opposed to the smaller pilot balloons, but, as the whole problem is essentially one, it is necessary

* The numbers in brackets refer to the bibliography on p. 23.

[*To face page* 2

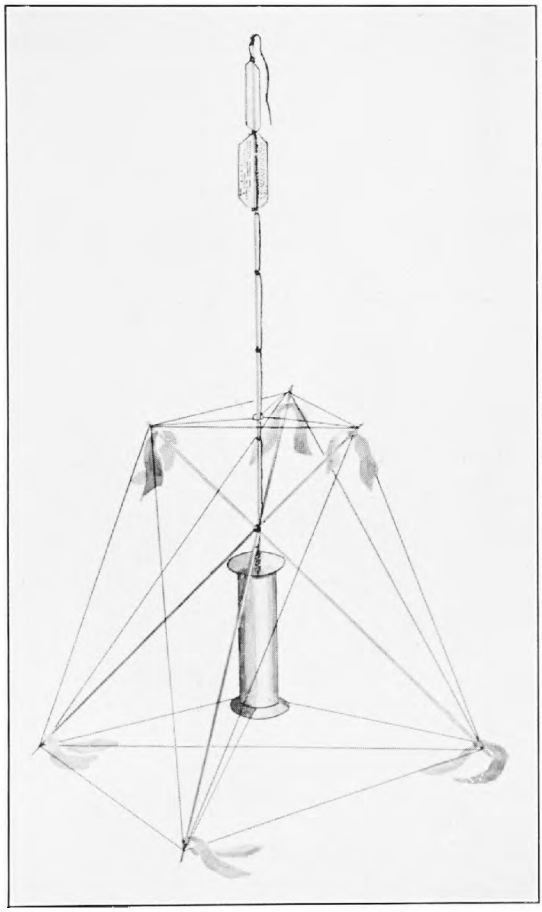

FIG. 1.—THE DINES METEOROGRAPH AND THE BAMBOO FRAME IN WHICH IT IS SECURED

to refer largely to the work of others on pilot balloons. As will presently be seen, the result of the present work is to modify and extend the conclusions reached by Hesselberg and Birkeland.

Early workers were accustomed to assume that the air resistance of a rubber balloon might be represented by an expression of the form

$$R = a.\rho.V^2.r^2$$

where R is the resistance, ρ is the density of the air, V is the velocity, r is the radius of the balloon (assumed spherical) and a is a constant. See Mallock (3) and J. S. Dines (4). Viscosity was thus assumed to be unimportant. The air resistance was also always measured in air of approximately normal density at the surface, a procedure which, though it is apparently arbitrary, is justified because it has been found that the vertical velocity of a free balloon varies little as it rises through the first few kilometres of the atmosphere.

Working on these simple lines J. S. Dines (4) evolved the formula

$$V = q\, L^{\frac{1}{2}}/(W + L)^{\frac{1}{2}}$$

where V is the velocity, L is the free lift of the balloon and attached apparatus (if any) when filled and ready to start, W is the weight of the balloon and attached apparatus, and q is a so-called constant. The evolution of this formula (4) shows that we may write it thus—

$$q = VP^{\frac{1}{2}}Q^{-\frac{1}{2}} \quad .. \quad .. \quad .. \quad .. \quad \text{(i)}$$

where Q is the air resistance of the balloon in grammes, and P is the difference between the weights of the enclosed gas and the air which it displaces.

The original value of q found by J. S. Dines was based on observations of balloons weighing 12 gm. or less. In course of time it was found that q was not constant, but that it tended to increase with the size of the balloon. Furthermore, if a balloon were loaded with a weight at the neck a larger value of q was applicable than in the case of a similar unloaded balloon. See papers by Capt. C. J. P. Cave and J. S. Dines (5) and Hesselberg and Birkeland (2). The reason for the higher velocity of the loaded balloon appears to be that the load checks the rolling which is such a prominent characteristic of an entirely free balloon, and that this rolling is associated with an increase in the turbulence produced in the air stream. Observations with sounding balloons weighing about 750 gm., made in England from time to time, have shown that the value of q applicable in that case is about twice as great as the value found by J. S. Dines for small pilot balloons.

Since J. S. Dines's formula took no account of viscosity, an attempt was made to harmonize the accumulated data by assuming a formula for the resistance of a sphere based on the equation—

$$R = a'\,(Vr)^2 + b'\,(Vr),$$

where a' and b' are constants, and r is the radius as before. The result was unsatisfactory. After some trials it was found that much better results were obtained by modifying a method which had previously been used by Hesselberg and Birkeland, who plotted a certain function, which they denoted by a, against the Reynolds

number $\rho Vr/\eta$ (2). If it may be assumed that the hydrogen with which the balloons were inflated was always of the same degree of purity, then the function a is strictly proportional to Dines's function q, and for plotting purposes either may be used indifferently. In what follows it has been assumed that the hydrogen employed was of standard purity, with one exception, which is specifically mentioned. Since in every case the velocity has been measured under conditions of surface density and temperature, it follows that ρ and η are very nearly constants, and therefore the Reynolds number $\rho Vr/\eta$ is, to a close enough approximation, proportional to Vr. Also, under the same conditions, $(W+L)$ in Dines's formula is porportional to r^3 (4), so that $Vr = bV\,(W+L)^{\frac{1}{3}}$, where b is a constant. We may therefore equally well plot q against $V\,(W+L)^{\frac{1}{3}}$ as against the Reynolds number, without altering anything except the scale of the diagram.

Hesselberg and Birkeland (2) used data from unencumbered balloons, and also from balloons covered with nets; the latter were larger balloons than the former and all were included in the same diagram. They do not seem to have appreciated that the presence of the net might materially alter the type of resistance experienced, and they have deliberately excluded one observation with a large balloon without a net which was widely discordant from those with nets. In the English experiments no nets were used, and when they were plotted on the same diagram with the other available data, the result was a consistent whole, free from some of the peculiar features found by Hesselberg and Birkeland.

Sounding balloons carrying meteorographs belong to the weighted class; in applying the Dines formula we have to remember that not only must the extra weight be allowed for, but also the air resistance of the object carried. It is simpler to use the modified formula (i) in such cases.

Let us adopt the following notation:

V is the velocity of the balloon in m/sec.
L_1 is the free lift of the balloon alone, when filled, in gm.
W_1 is the weight of the balloon alone in gm.
u is the tension of the string carrying the meteorograph in gm.
w_1 is the weight of the meteorograph and bamboo frame in gm.
w_2 is the air resistance of the latter when near the ground and at velocity V, in gm.

We have at once $u = w_1 + w_2$; w_1 is known, and it will be shown later that w_2 may be approximately determined from the equation

$$w_2 = 2{\cdot}4\,V^2$$

Substituting in (i) we have

$$q = V\,(W_1 + L_1)^{\frac{1}{3}}\,(L_1 - u)^{-\frac{1}{3}} \qquad .. \qquad .. \quad \text{(ii)}$$

As regards sounding balloons the available material consists of 10 soundings made by W. H. Dines, followed by two theodolites (6) and 13 others made by, or in connexion with, the Upper Air Section of Kew Observatory during the last 10 years, followed by a single theodolite using the tail method. There is also one pilot sounding made by C. Britton at Shoeburyness in 1932 with a large weighted

balloon. In some of the soundings the balloon was seen to burst, in which cases a check on the height was provided by the meteorograph record. The velocities used were those observed over the first few kilometres. In observations of this kind many uncertainties exist, and the data of an individual sounding are liable to considerable casual errors.

The general conclusion reached has been that the vertical velocity seems to fall off somewhat with height, but different observers are not in agreement on this point (7). Leakage of gas is a possible cause, but if so it seems certain that it must be rather by diffusion than by the development of pinholes of a visible nature. When the latter form, the velocity falls off rapidly and during daylight the resulting features on the record are unmistakable; it is remarkable that on these occasions the balloon generally bursts in the end. All that can be said is that the present investigation shows that a gradual falling off of velocity sometimes occurs, and that the order of magnitude is about 10 per cent. at a height of 20 Km.

The data are set out in Table I. The first line gives the mean results of the 10 soundings made by W. H. Dines (6). They were a homogeneous series in which all the balloons used were of the same weight. It is implied by W. H. Dines that the hydrogen gas which he used was not pure, and he gives some figures from which a measure of its density can be estimated. His velocities have therefore been corrected to represent the velocities which would have been found if pure hydrogen had been used and the same free lifts given. The magnitude of this correction is only 3½ per cent. The next 13 lines refer to soundings made under the control of the Upper Air Section, the last line refers to the Shoeburyness balloon. The values of q in the last column have been computed by the aid of equation (ii).

TABLE 1.—VERTICAL VELOCITIES AND OTHER DATA OF SOUNDING BALLOONS, WHICH WERE FOLLOWED BY ONE OR MORE THEODOLITES

Weight of balloon alone. W_1	Weight of meteorograph and bamboo frame. w_1	Air resistance of meteorograph and frame near the surface. w_2	Observed vertical velocity near the start. V	Free lift of the balloon alone. L_1	$(W_1+L_1)^{\frac{1}{3}}$	$V(W_1+L_1)^{\frac{1}{3}}$	(L_1-u)	q
gm.	gm.	gm.	m/sec.	gm.				
230	85	20	3·40	365	8·42	2·86	260	1·81
770	120	60	4·93	700	11·37	5·61	520	2·46
735	120	70	5·37	700	11·24	6·04	510	2·67
750	120	75	5·63	840	11·67	6·57	645	2·59
355	120	30	3·33	390	9·06	3·02	240	1·94
750	140	70	5·33	845	11·68	6·23	635	2·47
590	140	60	5·00	695	10·87	5·44	495	2·44
760	140	60	5·08	845	11·70	5·95	645	2·34
570	140	35	3·72	595	10·52	3·91	420	1·91
760	140	40	4·07	735	11·43	4·65	555	1·97
570	140	40	4·08	595	10·52	4·29	415	2·11
550	140	35	3·87	635	10·58	4·09	460	1·91
550	140	45	4·33	545	10·30	4·46	360	2·35
440	140	60	5·00	745	10·58	5·29	545	2·27
740	1080	60*	5·33	1790	13·62	7·27	650	2·85

* Approximate only.

In Fig. 2 the values of q in Table I have been plotted against $V(W_1 + L_1)^{\frac{1}{3}}$ in the form of small circles. The small crosses represent the results of seven weighted balloons given by Hesselberg and Birkeland (2, p.318). These balloons weighed between 20 and 325 gm.; they were weighted at the neck but were otherwise

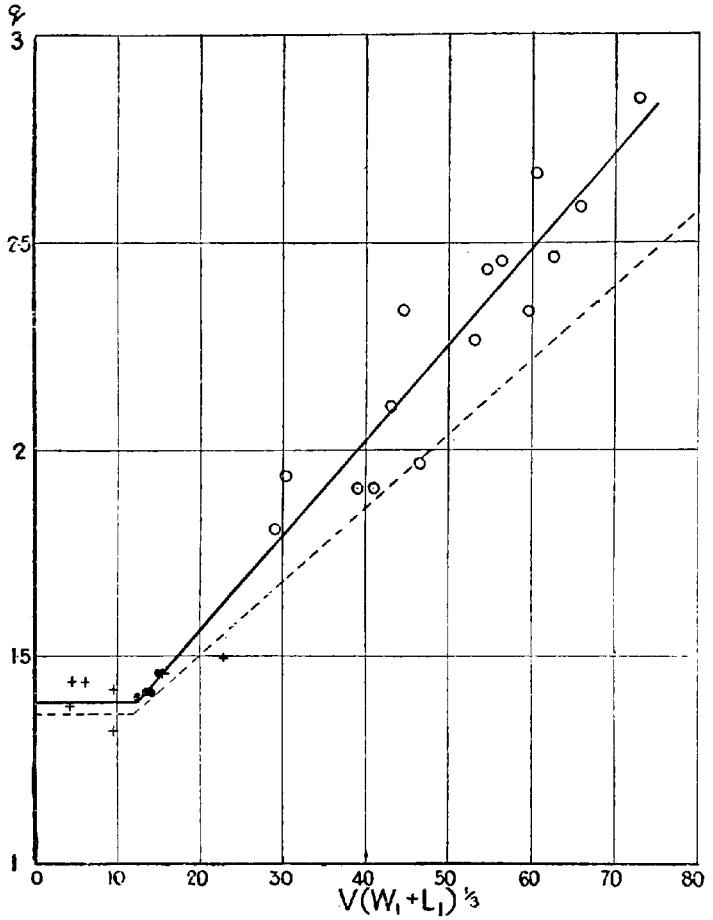

FIG. 2.—VALUES OF q FOR WEIGHTED BALLOONS IN METRE-GRAMME-SECOND (M.G.S.) UNITS PLOTTED AGAINST $V(W_1+L_1)^{\frac{1}{3}}$

unencumbered, the additional weights were approximately equal to the free lifts of the weighted balloons. The black dots refer to experiments with one weighted balloon made by Capt. C. J. P. Cave and J. S. Dines (5). The weight of the balloon was about 30 gm., and it was weighted in turn with a series of weights ranging up to about half the free lift of the unweighted balloon. It is convenient to defer the consideration of the interpretation of Fig. 2 till the related question of unweighted balloons has been dealt with.

Fig. 3 shows the results of observations with unweighted balloons, also unencumbered with nets. The small circles refer to

balloons of about 750 gm. weight observed by C. Britton by means of two theodolites and a long baseline (7). The velocities refer as before to the first few kilometres of the flight. The small crosses refer to observations made by several authorities, which are quoted

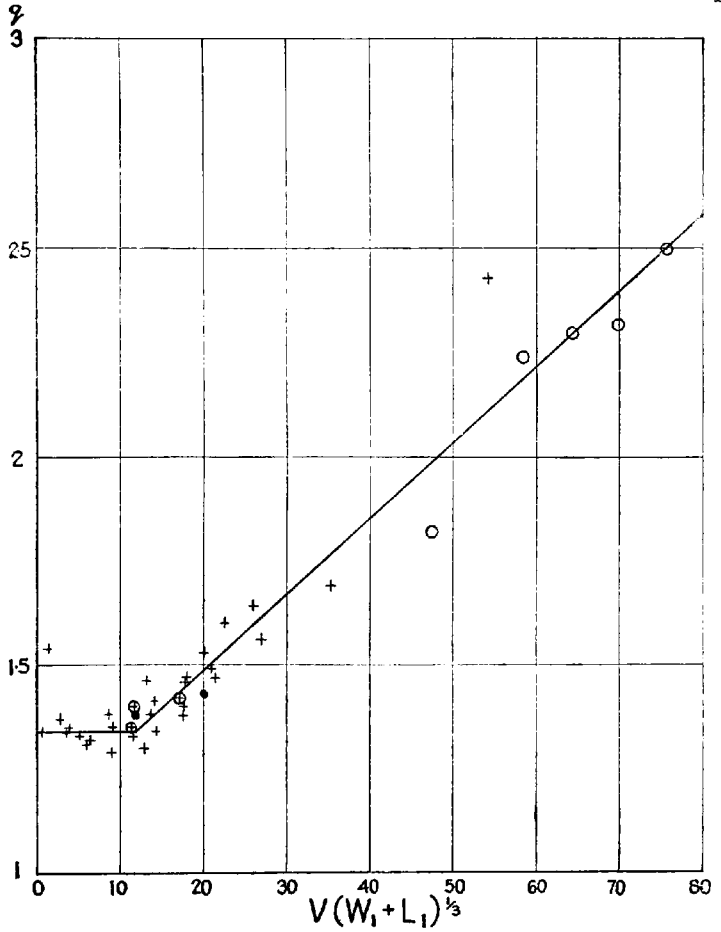

FIG. 3.—VALUES OF q FOR UNWEIGHTED BALLOONS IN M.G.S. UNITS PLOTTED AGAINST $V(W_1+L_1)^{\frac{1}{3}}$

by Hesselberg and Birkeland (2). The crossed circles are taken from Cave and Dines (5) and refer to three sizes of balloons. The black dots are taken from an article by Sherry and Waterman published in the United States *Monthly Weather Review* (8). These authors give a new formula for V, but do not give precise information about the weights or free lifts of the balloons to which it applies. All that could be done was to apply the formula to a few probable cases and plot the results.

It is possible to draw a mean curve with some measure of confidence at the lower end of the graph in Fig. 3, but with less certainty at the upper end ; in Fig. 2 the reverse is the case. If we

may assume that the general shape of the curve is the same for weighted and unweighted balloons, then the two supplement each other, and both can be drawn with tolerable accuracy. The thick lines are drawn on this basis, and for comparison that for unweighted balloons is reproduced in dotted form in Fig. 2. The shape of the mean curves is peculiar. The discontinuity when $V(W_1 + L_1)^{\frac{1}{3}}$ has a value of about 12 is the same as that found by Hesselberg and Birkeland, being based on the same data, but the second one found by them at about 17 disappears. There is no doubt that the reason for this is the absence of nets over the larger balloons in the present case.

We may in both Figs. 2 and 3 represent the mean curve with very fair accuracy by a short horizontal line between the abscissae 0 and 12·5, and a straight inclined line from 12·5 to the limit of the observations. Expressing these analytically we have from Fig. 2

$q = 1{\cdot}39$ when $V(W_1 + L_1)^{\frac{1}{3}}$ lies between 0 and 12·5.

$q = 1{\cdot}10 + {\cdot}0232\, V(W_1+L_1)^{\frac{1}{3}}$ when $V(W_1+L_1)^{\frac{1}{3}}$ lies between 12·5 and 75.

Now from equation (ii) $\quad q = V(W_1+L_1)^{\frac{1}{3}}(L_1-u)^{-\frac{1}{2}}$

Hence, by eliminating q we obtain expressions for V in terms of (L_1-u) and (W_1+L_1).

Repeating the same process with the data of Fig. 3 the following table is obtained :—

TABLE II.—VALUES OF V FOR SMOOTH RUBBER BALLOONS IN METRE-GRAMME-SECOND (M.G.S.) UNITS

	$V(W_1+L_1)^{\frac{1}{3}}$	V
Unweighted balloons	Between 0 and 12·0 ..	$1{\cdot}34\dfrac{(L_1-u)^{\frac{1}{2}}}{(W_1+L_1)^{\frac{1}{3}}}$
	Between 12·0 and 80 ..	$1{\cdot}12\dfrac{(L_1-u)^{\frac{1}{2}}}{(W_1+L_1)^{\frac{1}{3}}(1-{\cdot}0183(L_1-u)^{\frac{1}{2}})}$
Weighted balloons	Between 0 and 12·5 ..	$1{\cdot}39\dfrac{(L_1-u)^{\frac{1}{2}}}{(W_1+L_1)^{\frac{1}{3}}}$
	Between 12·5 and 75 ..	$1{\cdot}10\dfrac{(L_1-u)^{\frac{1}{2}}}{(W_1+L_1)^{\frac{1}{3}}(1-{\cdot}0232(L_1-u)^{\frac{1}{2}})}$

Another useful way of representing the results of Figs. 2 and 3 is to plot a graph of q against $(L_1 - u)$ and then to apply q in equation (ii). To do this we proceed as follows :—

From equation (ii) we have $\quad (L_1 - u) = V^2 (W_1+L_1)^{\frac{1}{3}} q^{-2}$.

Now in both Fig. 2 and Fig. 3 the ratio $V(W_1+L_1)^{\frac{1}{3}}/q$ represents a straight line through the origin of co-ordinates and therefore we can find a unique point on the mean line corresponding with any

definite value of $(L_1 - u)$. The appropriate value of q can then be read off. The graphs in Fig. 4 have been formed in this manner; they have the advantage that they can readily be extended to

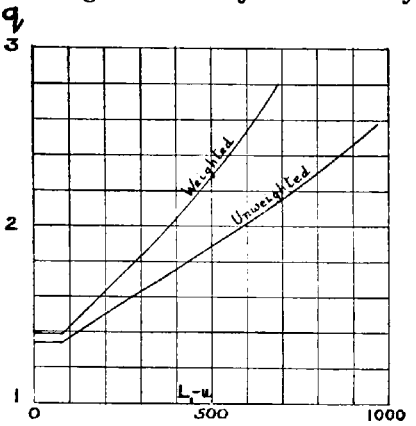

FIG. 4.—VALUES OF q IN M.G.S. UNITS PLOTTED AGAINST $(L_1 - u)$

include a further range of values of $(L_1 - u)$ as more data become available from observations of large balloons. The practical problem is to determine V when W_1, L_1 and u are known. Table II enables this to be done, but is awkward for purposes of computing. A better way is to plot Table II in the form of isopleths of V, using $(W_1 + L_1)$ and $(L_1 - u)$ as co-ordinates. Fig. 5 has been formed in this way, covering a portion of Table II for weighted balloons.

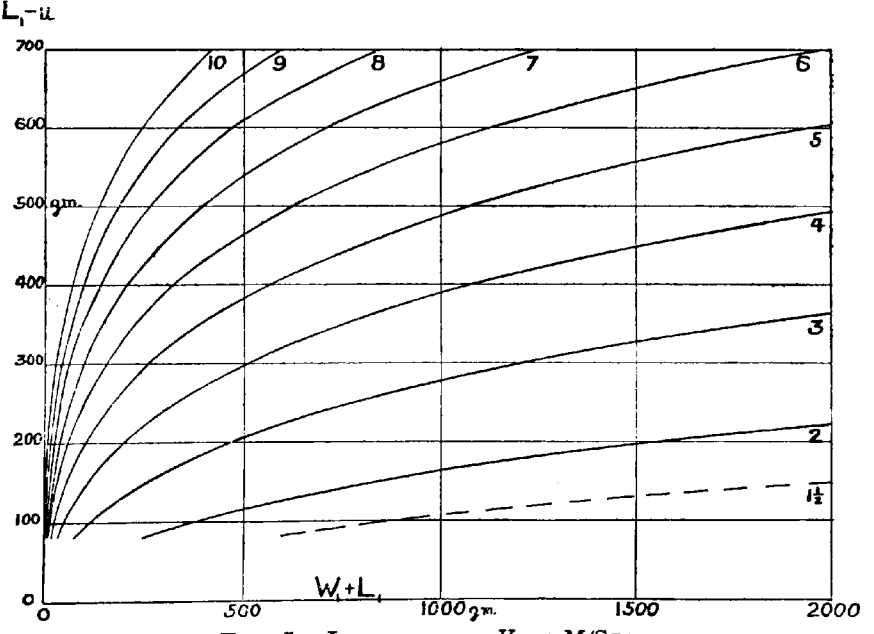

FIG. 5.—ISOPLETHS OF V IN M/SEC.

Since the problem under discussion is essentially that of the fluid resistance of a sphere, it is convenient also to express Table II in the form of resistance formulae in C.G.S. units.

To do this we remember that,

$(L_1 - u)$ = the fluid resistance of the sphere in gm. weight.

$(W_1 + L_1) = \frac{4}{3}\pi r^3 (\rho_a - \rho_h)$, where ρ_a and ρ_h are the densities of air and hydrogen at the normal temperature and pressure at the surface.

V = velocity in metres per sec.

Assuming pure hydrogen to be employed in filling the balloons we have,

$(\rho_a - \rho_h) = \cdot 001159$ in C.G.S. units.

Whence $(W_1 + L_1) = r^3(\cdot 004861)$, where r is the radius of the sphere in cm.

Also $R = g.(L_1 - u)$ where R is the resistance in dynes, and $100.V = v$, where v is the velocity in cm./sec.

Then by arithmetic and algebra the following table may be deduced from the expressions in Table II.

TABLE III.—VALUES OF THE AIR RESISTANCE IN DYNES FOR SMOOTH RUBBER BALLOONS IN AIR OF DENSITY 1247×10^{-6}

	vr	R
Unweighted balloons	Between 0 and 7090 ..	$(0 \cdot 80) \cdot (\frac{1}{2}\pi\rho_a v^2 r^2)$
	Between 7090 and 47000	$(0 \cdot 80) \cdot (\frac{1}{2}\pi\rho_a v^2 r^2) \cdot \left(1 + \frac{vr - 7090}{43220}\right)^{-2}$
Weighted balloons	Between 0 and 7370 ..	$(0 \cdot 74) \cdot (\frac{1}{2}\pi\rho_a v^2 r^2)$
	Between 7370 and 44000	$(0 \cdot 74) \cdot (\frac{1}{2}\pi\rho_a v^2 r^2) \cdot \left(1 + \frac{vr - 7370}{35350}\right)^{-2}$

The motion of an ascending rubber balloon of any size is always unstable and does not give the impression of streamline flow. The discontinuity shown in Table III when vr is about 7000 can hardly, therefore, denote a change from streamline to turbulent flow; it must rather be associated with a change in the manner of the turbulence at this point. It is evident that the formulae in Table III cannot remain valid as vr goes on increasing, for in that case R would ultimately become independent of vr. It is therefore not safe to extrapolate them beyond the limits stated.

II.—The falling velocity of the burst balloon and meteorograph

It remains to be considered what happens in the case of soundings made with the Dines meteorograph after the balloon has burst. Evidence on this point has been obtained in several ways and it is possible to come to some general conclusions.

It is first necessary to determine the rate of fall of a meteorograph and bamboo frame alone, unencumbered by the remains of the burst balloon. To this end a standard apparatus was allowed to fall to the ground from various heights and the mean time of fall for each height determined by a stop-watch. The tests were mainly made from the Pagoda in Kew Gardens. If we assume for the moment that a body of this kind experiences air resistance according to the law $R \propto \rho_a v^2$, then the final steady velocity can be determined by means of the equation

$$v^2_s \log \cosh(gt/v_s) = gs$$

where t is the time of fall, s is the total drop, and v_s is the final steady velocity in cm./sec., in air of the same density. This equation may be solved with the aid of tables and a graph, or by approximate means. The results of three tests are set out in Table IV.

TABLE IV.—DATA OF TESTS OF THE FINAL STEADY VELOCITY OF THE FALLING METEOROGRAPH WHEN NEAR THE GROUND

Site.	Weight of the falling apparatus.	Total drop.	Time of fall.	Final steady velocity (computed).	Final steady velocity of similar apparatus weighing 135 gm.
	gm.	m.	sec.	m./sec.	m./sec.
Kew Observatory	135	18·9	3·05	7·5	7·5
Pagoda	147	30·0	4·42	7·7	7·4
,,	147	40·0	5·57	8·0	7·6

It will be noticed that the weight of the apparatus was not quite the same in the three cases, but the form and air resistance differed little. Assuming that the air resistance is proportional to the square of the velocity we may reduce the last two tests to the conditions of the first, which has been done in the right-hand column. The mean final steady velocity for an apparatus weighing 135 gm. may be taken as 7·5 m/sec.

On the assumption made above it is now possible to determine the approximate rate of fall at any height above the ground by applying the known mean values of the air density. This has been done, and the results are set out in the second row of Table V.

TABLE V.—VELOCITY AND TIME OF FALL OF THE METEOROGRAPH AND BAMBOO FRAME WHEN FALLING FREELY

Height above M.S.L. Km.	0	2	4	6	8	10	12	14	16	18	20	22	24
Factor of density of the air	1	·81	·65	·53	·42	·33	·24	·18	·13	·095	·070	·051	·039
Velocity of fall. (Uncorrected) .. m./sec.	7·5	8·3	9·3	10·3	11·6	13·1	15·3	17·7	20·8	24·4	28·4	33·2	38·0
Velocity of fall. (Corrected) .. m/sec.	7·5	8·3	9·3	10·3	11·6	13·0	15·1	17·4	20·4	23·7	27·4	31·7	36·1
Time of fall to M.S.L. (Corrected) min.	0	4	8	11	14	17	20	22	23	25	26	27	28
Mean velocity of fall to M.S.L. (Corrected) .. m/sec.	7·5	7·9	8·3	8·8	9·2	9·7	10·2	10·8	11·4	12·1	12·7	13·4	14·1

It is necessary to test the validity of the assumption which has been made as regards the law of resistance. Essentially the apparatus consists of thin bamboo sticks about 4 mm. in diameter, cotton threads about $\frac{1}{2}$ mm. thick, small silk flags, and the solid body of the meteorograph. Of these the effective cross section presented to the air is roughly as follows :—

Cotton threads and silk flags ..	27 per cent.
Bamboos	37 ,,
Meteorograph	36 ,,

If the velocities given in the second row of Table V be taken as a basis, then reference to Smithsonian Tables (8th revised edition, 1933), Tables 159 and 161, shows that we may expect the solid body of the meteorograph to be little affected by the viscosity of the air up to the 24 Km. level, but the other components will to some extent be so in the upper levels. It may be estimated approximately that, for the complete apparatus, if $R/\rho v^2$ be counted as unity at the surface, then its value at 16, 20 and 24 Km. will be about 1·04, 1·07 and 1·10 respectively. This implies that the velocities at those heights will be less than those shown in the second row by 2 per cent., $3\frac{1}{2}$ per cent., and 5 per cent. respectively. The third, fourth and fifth rows of Table V have been computed on this basis.

In an actual sounding, if the remains of the burst balloon had not to be considered, the velocity and time of fall could be estimated directly from Table V, but there is no reason to suppose that the remains of the balloon fall at the same rate as the meteorograph alone. Balloons vary in size and in the thickness of the rubber walls and the rate of fall varies considerably in different cases.

Some experiments were made of throwing a particular burst balloon from the top of Kew Observatory and timing the fall with a stop-watch. From them a final steady velocity of about 5 m./sec. was deduced. When a weight of 30 gm. was tied to one corner the rate increased by about 6 per cent.

On two occasions balloons seen to burst were followed by the theodolite for a few minutes afterwards, and it was possible in that way to estimate the velocity of fall. One observation suggested a velocity of 11 m./sec. at a height of 19 Km., the other, less definite, about $11\frac{1}{2}$ m./sec. at 21 Km. There are records available of eight occasions on which the balloon is known to have burst, and the finder also gave information from which the instant of reaching the ground could be determined, or at least estimated. In so far as this information can be relied on, the total time of flight can be determined, and if the velocity of ascent can be estimated the time of bursting can be determined from the known height. Hence, the duration and mean velocity of the fall can be computed. The results of the eight soundings are set out in Table VI.

TABLE VI. — DATA OF EIGHT SOUNDINGS OF WHICH THE TOTAL TIME OF FLIGHT IS KNOWN

No.	Total time of flight.	Height at instant of burst.	L_1-u	W_1+L_1	Velocity of ascent, computed.	Duration of ascent, computed.	Duration of descent, computed.	Mean velocity of descent.
	min.	Km.	gm.	gm.	m./sec.	min.	min.	m./sec.
1	98	22·5	500	1,420	4·56	82	16	23·4
2	105	16·0	515	1,390	4·71	57	48	5·6
3	90	14·4	425	1,125	4·18	58	32	7·4
4	115	19·9	515	1,570	4·53	73	42	7·9
5	190	17·7	515	1,530	4·56	65	125	2·4
6	195	25·0	515	1,440	4·66	90	105	4·0
7	80	16·6	515	1,480	4·63	60	20	13·8
8	98	19·0	615	1,460	5·91	54	44	7·3

A large range of mean falling velocities is shown in Table VI. The first entry looks too large while the fifth looks incredibly small. The last two are interesting because in both cases the finders reported that they saw the apparatus come down balloon foremost. This is understandable in the first of the two where the velocity was very high, but not in the second where it was not. Probably the best thing to do is to form a mean of such observations as we have, but to omit the two extreme cases in Table VI. This has been done in Table VII, where the observed velocity of fall, either at some particular height or a mean over the whole distance, is compared with the corresponding velocity of fall for the meteorograph alone under similar conditions, determined from Table V.

TABLE VII.—COMPARISON BETWEEN THE FALLING VELOCITY OF THE BURST BALLOON AND METEOROGRAPH AND THAT OF THE METEOROGRAPH ALONE.

Source of information.	Ratio $\frac{\text{Velocity of fall.}}{\text{Velocity of meteorograph}}$
Table 6, No. 2	0·49
,, No. 3	0·68
,, No. 4	0·62
,, No. 6	0·28
,, No. 7	1·19
,, No. 8	0·59
Theodolite observation at 19 Km. ..	0·43
Theodolite observation at 21 Km. ..	0·39
Burst balloon thrown from a height ..	0·70
Mean value of ratio	0·60

The table shows a wide range of values, but how far these are genuine or how far they are due to errors of observation is not known. Taking the figures at their face value it appears that the falling velocity in a given case may lie between 0·3 and 1·2 of that for the meteorograph alone, as shown in Table V. This suggests a minimum falling velocity of 8 m./sec. at 20 Km. and of $2\frac{1}{2}$ m./sec. near the ground; it seems very unlikely that the velocities can be less than these.

It is sometimes useful to make an estimate of the falling velocity of the burst balloon and meteorograph, even though it be only approximate. To that end Table VIII has been computed by applying to the corrected velocity of fall given in Table V the factor 0·6, which was found to be the mean value of the ratio in Table VII. Thence, in the last row of Table VIII, the time of fall to M.S.L. has also been determined.

TABLE VIII.—VELOCITY OF FALL OF THE BURST BALLOON AND METEOROGRAPH AT DIFFERENT HEIGHTS, AND TIME OF FALL TO MEAN SEA LEVEL.

Height above M.S.L., Km.	0	2	4	6	8	10	12	14	16	18	20	22	24
Velocity of fall .. m./sec.	5	5	6	6	7	8	9	10	12	14	16	19	22
Time of fall to M.S.L. min.	0	7	13	18	23	28	33	37	39	42	43	45	47

In computing Table VIII the assumption has been made that the air resistance of the burst balloon follows the same law as that of the meteorograph and frame; this is not likely to be exactly the

case. The approximate accuracy of the table is not likely to be greatly affected because the times of fall from the greater heights are chiefly based on independent observations derived from Table VI.

Table IX gives the total time of flight from start to finish for various rates of ascent, on the assumption of a constant rate of ascent and a time of fall as given in Table VIII.

TABLE IX.—TOTAL TIME OF FLIGHT IN MINUTES.

Velocity of ascent. m./sec.	3	4	5	6	7
Height, Km.		Minutes.			
2	18	16	14	13	12
4	35	30	26	24	23
6	51	43	38	35	32
8	67	56	50	45	42
10	84	70	61	56	52
12	100	83	73	66	62
14	115	95	84	76	70
16	128	106	92	84	77
18	142	117	102	92	85
20	154	126	110	99	91
22	167	137	118	106	97
24	180	147	127	114	104

III.—The effect of Solar Radiation on the records of temperature obtained by means of sounding balloons.

When sounding balloons carrying meteorographs are sent up in the daytime the question frequently arises whether the temperatures recorded represent the true temperature of the air, or whether owing to solar radiation falling on the instrument, they are systematically too high. This matter has engaged the attention of the Upper Air Section of Kew Observatory more than once in connexion with the soundings made in England, but the results of these investigations have not heretofore been published.

The recording apparatus employed is fully described in the pamphlet previously referred to (1). It is sufficient to state here that the thermograph consists of a strip of nickel silver working in conjunction with an invar rod. The strip is 0·15 mm. in thickness by 13 cm. in length, and is protected from external radiation by being placed in a cylindrical aluminium tube 7 cm. in diameter by 24 cm. in length. The outer surface is polished and the ends of the tube are coned outward in order to induce a better draught of air through it. The whole apparatus is suspended from the balloon by a thin cord 40 metres in length; the axis of the tube is vertical, and ventilation is effected solely by the relative vertical velocity through the air.

The balloons employed were of various sizes, weighing from 250 to 850 gm., and the velocities with which they ascended and descended have been indicated in Parts I and II. In general the velocity of ascent may be taken to have lain between 3 and 5 m./sec., sometimes a little more perhaps and sometimes, near the top, rather less. Near the ground the velocity of descent was on the average rather greater than that of ascent; in the stratosphere the falling velocity was much greater than the rising one, being at a height of 20 Km. at least twice and generally three times as great.

The ventilating power of the air may be taken to be roughly indicated by the product of the velocity and the density. The density at 20 Km. is 0·07 of its value at the surface, which means that on the ascent the ventilation at 20 Km. has one-fourteenth of its value at the surface, or even less. On the descent the conditions are better and it may be inferred from Table VIII that the ventilating power at 20 Km. is about a quarter of that on the ascent near the surface. It must also be remembered that the ventilation grows steadily worse with increasing height both on ascent and descent, while the intensity of the solar radiation tends if anything to increase.

Under these conditions it is to be expected that the record of temperature made on the ascent will be higher than that on the descent when soundings are made into the stratosphere in daylight, but it is not *prima facie* possible to say what the residual error on the descent will be. A study of any series of records made by the Dines meteorograph shows that in the troposphere there is a systematic tendency for the temperature on the ascent to be higher than that on the descent both by day and night; for a few kilometres above the tropopause the tendency disappears, but in the upper parts of any sounding which penetrates well into the stratosphere the tendency reappears, but only when the sun is above the horizon. After sunset there is no systematic difference in the upper parts of the stratosphere and in such cases there can be little doubt that the recorded temperature is close to the true temperature of the air.

It may be objected that since the apparatus does not rise and fall through the same masses of air, there is no reason why the two records should agree. What we have to explain, however, is a systematic difference, which it is impossible to associate with the air masses concerned.

Dealing first with the temperature in the troposphere, it is almost always found that the ascent is from 1°A to 4°A warmer than the descent. J. H. Field has shown (9) that lag of the thermograph would produce results of this kind, and that the mean of the two records will be close to the true air temperature provided that the effect of solar radiation is negligible. One way of testing this is to compare the mean magnitude of the difference between ascent and descent with the time of day at which the sounding was made. It is evident from Parts I and II of the present paper that the ventilation is much better on the descent than on the ascent, and

therefore if direct solar radiation affects the thermograph appreciably there will be a greater difference by day than by night. About 10 years ago some 68 soundings, made over a period of two years, were analysed in this way, and the results are set out in Table X. Here $\Delta\theta$ is the mean difference in °A between the ascending and descending records for that portion of the troposphere lying between the 3 Km. level and the tropopause. The time of the sounding is reckoned to be the instant when the instrument reached the tropopause on the ascent.

TABLE X.—DIFFERENCE BETWEEN TEMPERATURE ON ASCENT AND DESCENT IN °A IN RELATION TO THE TIME WHEN THE SOUNDING WAS MADE.

	Hours after sunset or before sunrise.			Hours before sunset or after sunrise.				
Time of sounding ..	6 to 2	2 to 1	1 to 0	0 to 1	1 to 2	2 to 3	3 to 5	5 to 8
$\Delta\theta$ in Summer	3·0	—	1·7	2·4	2·0	2·3	1·7	2·2
No. of soundings	(1)	(0)	(7)	(5)	(3)	(7)	(11)	(3)
$\Delta\theta$ in Winter	—	1·6	1·7	2·0	1·8	2·7	2·3	2·7
No. of soundings	(0)	(7)	(7)	(3)	(6)	(2)	(3)	(3)

Examining Table X it is perhaps just possible to say that $\Delta\theta$ is greater by day than by night, but the mean difference is not more than 0·3°. It may be inferred that the effect of solar radiation must be small as far as the troposphere is concerned, probably not more than 1°A on the average.

Turning next to the stratosphere we find that an entirely different set of conditions exists. The lapse rate is small and lag of the thermograph cannot account for differences between ascent and descent. A recent inquiry covered the period of 11 years from 1923 to 1933, including all soundings reaching at least 17 Km. One hundred and fifty-five such soundings were found and classified according to the month in which they were made. They were then further subdivided into two classes, day and night. The former comprise those which started after sunrise and not later than about one hour before sunset, the latter those which started either in the evening, less than one hour before sunset, or any time in the night before sunrise. The distinction between the two classes is somewhat arbitrary and is not in every case perfectly satisfactory, but it provides a rough means of separating them and, as will be shown later, leads to definite results. In some of the summer months there were no night soundings available, and in some winter months very few day ones. In each case the record of temperature on both ascent and descent was read at heights of 13, 15 and 17 Km., and where available at 19 Km. also. From considerations of space the figures are not given in full, but a summary in the form of means is given in Table XI.

TABLE XI.—HIGH SOUNDINGS DURING THE YEARS 1923 TO 1933. MONTHLY MEAN TEMPERATURES 200°A +, NIGHT AND DAY, ASCENT AND DESCENT.

		Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
13 Km.	Night A	(3) 11·7	(5) 13·6	(4) 17·0	(0) —	(3) 26·3	(0) —	(0) —	(1) 19·0	(8) 14·6	(3) 16·0	(7) 19·3	(12) 13·9
	Night D	12·3	14·2	16·0	—	25·3	—	—	19·0	14·1	15·7	18·4	14·1
	Day A	(2) 18·5	(5) 15·2	(8) 20·4	(6) 21·7	(16) 22·1	(15) 22·7	(17) 22·0	(15) 20·8	(13) 18·3	(11) 19·4	(3) 22·3	(1) 10·0
	Day D	17·0	13·6	20·6	21·3	20·4	22·1	20·7	19·7	16·9	17·7	20·3	10·0
15 Km.	Night A	(3) 14·0	(5) 15·6	(4) 16·3	(0) —	(3) 25·7	(0) —	(0) —	(1) 19·0	(8) 15·0	(3) 14·7	(7) 16·0	(12) 13·2
	Night D	12·7	15·2	15·5	—	24·0	—	—	19·0	15·0	14·7	15·6	13·3
	Day A	(2) 18·5	(5) 18·2	(8) 21·5	(6) 22·7	(16) 22·1	(15) 23·5	(13) 22·5	(15) 23·3	(13) 19·5	(11) 17·8	(3) 20·3	(1) 13·0
	Day D	16·0	15·0	19·7	20·3	19·9	21·7	21·2	21·7	16·9	15·4	18·0	12·0
17 Km.	Night A	(3) 14·0	(5) 14·4	(4) 14·7	(0) —	(3) 24·0	(0) —	(0) —	(1) 20·0	(8) 16·0	(3) 15·3	(7) 15·1	(12) 11·7
	Night D	13·3	14·4	14·5	—	23·3	—	—	20·0	16·0	15·3	14·3	11·3
	Day A	(2) 19·0	(5) 19·4	(8) 21·4	(6) 22·0	(17) 23·6	(15) 24·5	(13) 24·2	(15) 25·6	(13) 22·2	(11) 19·4	(3) 18·7	(1) 13·0
	Day D	16·0	15·4	19·3	20·0	20·3	22·3	22·2	22·9	19·4	17·6	17·7	9·0
19 Km.	Night A	(2) 15·5	(3) 15·0	(2) 12·0	(0) —	(1) 20·0	(0) —	(0) —	(1) 23·0	(3) 17·7	(2) 15·5	(2) 15·5	(5) 12·2
	Night D	15·5	15·0	12·0	—	19·0	—	—	23·0	17·3	15·5	14·5	11·0
	Day A	(1) 17·0	(1) 12·0	(5) 23·8	(2) 24·5	(10) 26·5	(7) 25·4	(9) 27·7	(8) 28·1	(5) 25·0	(7) 21·0	(1) 20·0	(0) —
	Day D	16·0	12·0	21·4	18·0	21·5	23·4	24·6	25·1	20·6	17·4	14·0	- -

NOTE.—Numbers in brackets denote number of observations.

It will be seen that there are 35 sets of monthly means available from which it is possible to compare day with night; of these, 25 show the temperatures recorded at night on both ascent and descent to be each less than the corresponding temperatures by day. Of the remaining 10, only three have any significance in the opposite direction, the remaining seven being mostly based on very few observations.

The figures in Table XI are further analysed in Table XII.

TABLE XII.—ANNUAL WEIGHTED MEANS OF MONTHLY MEAN DIFFERENCES OF RECORDED TEMPERATURE

	Height in Km.			
	13	15	17	19
Temperature at night. Ascent less descent .. .. .. °A.	0·2	0·3	0·3	0·4
Temperature by day. Ascent less descent .. .. .. °A.	1·1	2·0	2·5	3·5
Temperature on ascent. Day less night .. .. .. °A.	2·1	2·9	4·4	6·0
Temperature on descent. Day less night .. .. .. °A.	1·2	1·1	2·0	2·8

In the first two rows of Table XII the weighting factor is the number of observations in the month. In the last two a different factor had to be employed because the number of observations was generally different for the two elements compared In such cases the following rule has been used to determine the weighting factor :—

If n_1 be the number of day soundings in a given month and n_2 the number of night soundings in the same month, then the weighting factor for that month is deemed to be equal to

$$2\,n_1\,n_2/(n_1 + n_2)$$

This rule is based on the assumption that all the observations are liable to approximately the same probable departure from the true mean of their class. The manner of its operation can be seen from the fact that if n_1 and n_2 are equal, the factor reduces to n_1 also. If either n_1 or n_2 is equal to 1 while the other is large, the factor becomes nearly equal to 2.

In consequence of the different methods of forming the weighted means in the two parts of Table XII the table is not quite self-consistent, but the discrepancies are small and do not affect the general result.

In Fig. 6 there are shown graphically the relations between the following four quantities :—

Temperature at night on the descent.
Temperature at night on the ascent.
Temperature by day on the descent.
Temperature by day on the ascent.

The first is taken as the datum because it gives the best estimate of the temperature of the air, the others are shown in relation to it according to the figures of Table XII. The upper curve can be arrived at in two ways from Table XII, and both are therefore shown dotted. The difference between them is insignificant.

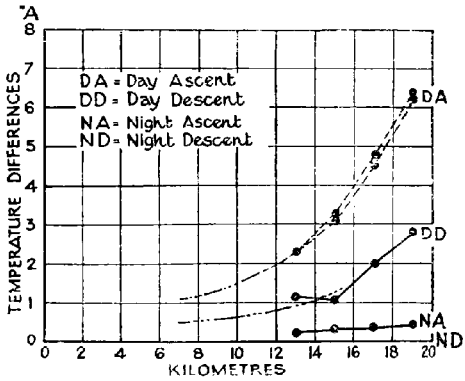

FIG. 6—RELATION BETWEEN THE TEMPERATURES RECORDED ON THE ASCENTS AND DESCENTS OF DAY AND NIGHT SOUNDINGS.

The curves in Fig. 6 are remarkable. The night temperatures agree fairly closely as between ascent and descent, and such difference as exists is probably partly due to the fact that under the system of classification adopted the sun was not always below the horizon when the observations were made. The day temperatures show a progressive difference increasing with height exactly as would be expected if solar radiation were the cause. The question arises whether the recorded difference between day and night can be due to a diurnal variation of temperature at these levels. A little consideration shows that this can hardly be the explanation of the figures. The greater number of the night soundings were made near 18 h. G.M.T., while large numbers of the day ones were made near 7 h. G.M.T. If we admit the possibility of a large diurnal range of temperature at the levels of 15 and 17 Km., it would seem certain that the maximum must be in the afternoon or evening and the minimum at sunrise. The figures, however, show the exact opposite.

Fig. 6 suggests that errors due to radiation become small below 10 Km. This fits in well with the independent estimate which was made above from a consideration of Table X. The data of the latter

table may be taken to refer to an average height of about 7 Km., and the estimated mean effect of solar radiation there was something less than 1°A. One may therefore extrapolate the day curves in Fig. 6 on this basis, which has been done in the chain-dotted extensions shown.

It has been the practice of the Upper Air Section of Kew Observatory for many years to give greater weight to the record of temperature on the descent than on the ascent in the upper parts of high daylight soundings. While this process has minimised the effect of solar radiation, yet it is probable from the slope of the curve of day descent that at heights exceeding 20 Km. there are possibilities of serious error, even if the descent only be used.

It is worth inquiring what the immediate process is by which the solar radiation raises the temperature of the thermograph above that of the surrounding air. It cannot be due to the heating of the balloon, since that is 40 metres distant; one cause may be the heating of the tubular aluminium case and the part of the bamboo framework just above it, another, the entry of radiation at the top end of the case and subsequent reflections inside. Experiments made to test the former have yielded negative results, and at present the latter seems to be the more likely.

A further possibility is that in the stratosphere when a solid sheet of cloud exists lower down there may be considerable vertical radiation reflected from the upper surface of the clouds; such must exist and to some extent must affect the thermograph, which is unprotected from vertical rays, the only question is whether it has any appreciable magnitude. In order to test the matter the four months June to September were selected during which the mean temperature at 17 Km. does not vary much. Thirty-eight soundings were found in which the instrument was known to be in direct sunshine, and these were classified according to the amount of the sky covered with clouds at the start. The results are set out in Table XIII, which shows the temperature at 15 and 17 Km. under various conditions of cloudiness.

TABLE XIII.—SOUNDINGS IN THE MONTHS JUNE–SEPTEMBER, CLASSIFIED ACCORDING TO THE CLOUDINESS OF THE SKY AT THE START.

State of Sky, 0–10.	0, 1, 2	3, 4	5, 6	7, 8	9, 10
Temperature at 15 Km. Mean of ascent and descent .. .. 200° A+	21·6	24·7	22·0	22·3	22·7
Temperature at 17 Km. Mean of ascent and descent .. .. 200° A+	23·0	26·4	23·2	23·5	24·2
Temperature on ascent only. Mean at 15 and 17 Km. .. 200° A+	23·2	26·9	23·7	24·4	24·6
No. of observations	8	5	2	9	14

No systematic difference can be detected in the mean temperatures at either 15 or 17 Km. as the amount of cloud varies. Although the number of observations is not large, the table at least shows that the effect of reflected radiation from clouds must be small compared with that of direct radiation from the sun.

Several points were noticed in the course of the analysis of the data used in the formation of Table XIII. It was found that both at 15 and 17 Km. the difference between the temperatures recorded on ascent and descent was much the same whether the sounding was made near midday or much nearer sunrise or sunset. There was also no indication that the temperatures were higher near midday than at other times. On the other hand, when small balloons were used the temperatures were a little higher than with larger ones; this was due, no doubt, to the lesser vertical velocity of the small balloons. There seems to be some ground for inferring that as regards the effect of solar radiation on the thermograph, the altitude of the sun has not very much importance in the stratosphere. This is no doubt due to the small density of the air, by which much less radiative energy is absorbed when the sun's altitude is low than is the case at the surface. It should be mentioned here that the standard Dines meteorograph case is not suitable for midday observations in the tropics, since there is no protection of the thermograph against rays having an elevation of 80 or 90 degrees.

In examining the temperature-pressure graphs which formed the basis of this investigation, it was noticed that large differences between the temperatures recorded on the ascent and descent in the stratosphere are much less likely to occur when soundings are made near 18 h. G.M.T. than in the case of soundings made near 7 h. G.M.T. This is true even in the summer months. There is nothing to be surprised at in this, because the balloon takes about an hour to reach 16 Km. and therefore the sounding made at 18 h. in England has the advantage of three hours over that made at 7 h. in respect to the nearness of sunrise or sunset. It is clear that of the two hours, 7 and 18, the latter has the advantage from the point of view of accurate measurement of temperature.

The use of larger balloons with consequent higher velocities, or the greater inflation of the balloons ordinarily used would do something to decrease the effect of solar radiation on the ascent, but it could not eliminate it. The curve of day descent in Fig. 6 is based on vertical velocities much higher than could be obtained on the ascent, but it suggests serious error at a height of 20 Km. Since all the predisposing causes of error increase with height it may be inferred that soundings reaching well above 20 Km. in the day time may be subject to still more serious error.

A simple screen capable of rendering the meteorograph immune to solar radiation in the low densities of the air at great heights is not easy to devise, and heretofore observers have almost universally compromised by using a simple polished tube similar to that of the

Dines meteorograph. It would appear that until a suitable screen has been brought into use a strong case can be made out for avoiding the making of very high soundings at the international hours of 7 h. and 13 h. G.M.T. At the present time, with improved balloons, greater heights can be reached than heretofore, and with increased interest in the conditions prevailing at heights of over 20 Km. it is important that no suspicions of error due to radiation should arise. This investigation has shown that such suspicions may sometimes be justified.

In the preparation of this paper, I am indebted to the kindness of Sir Arthur Hill, Director of Kew Gardens, who allowed the use of the Pagoda for experimental purposes; and to Dr. F. J. W. Whipple, Superintendent of Kew Observatory, who made many valuable suggestions.

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